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Computation and Validation of the Dynamic Response Index (DRI)

6 August 2013

Dacie Manion

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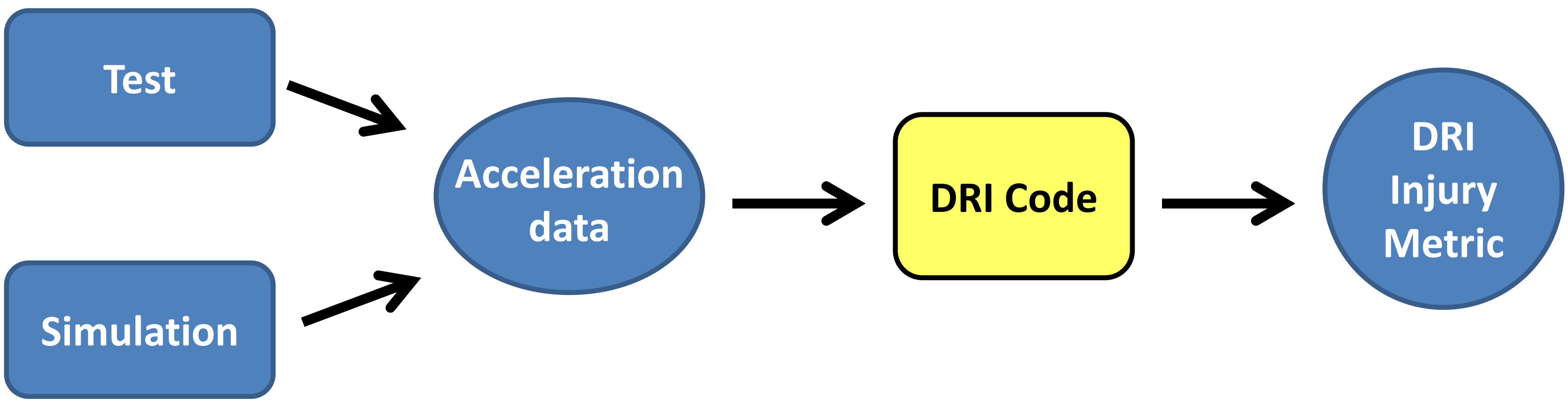
Introduction

- Motivation and background
- DRI overview
- 1-DOF and 3-DOF models
- Usage
- Validation
- EARTH metric
- Summary
- Ongoing work

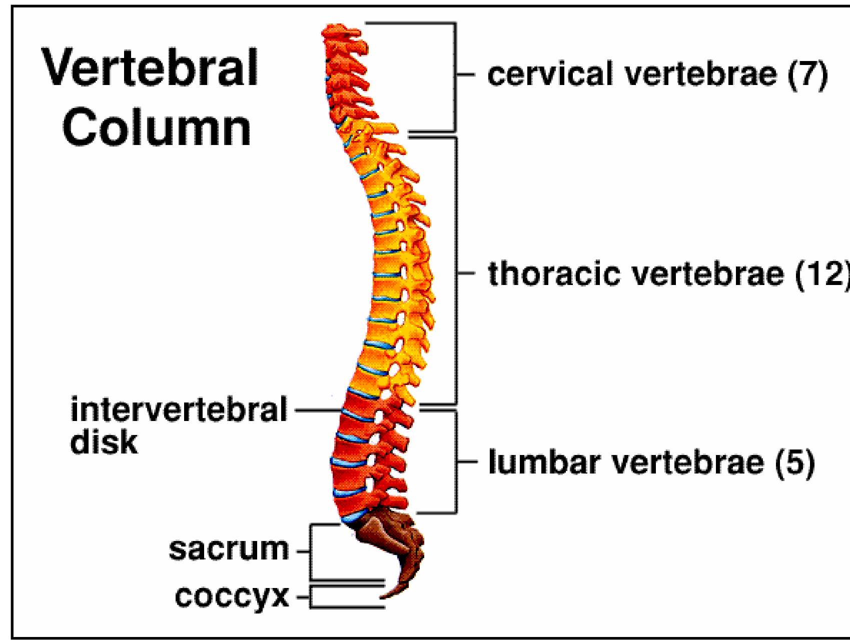
DRI Code: Motivation

- Develop a fast in-house code for calculating the **Dynamic Response Index (DRI) injury metric** using test or simulation results as input.
- Code should be **stand-alone** in nature and should lend itself easily to **process automation**.



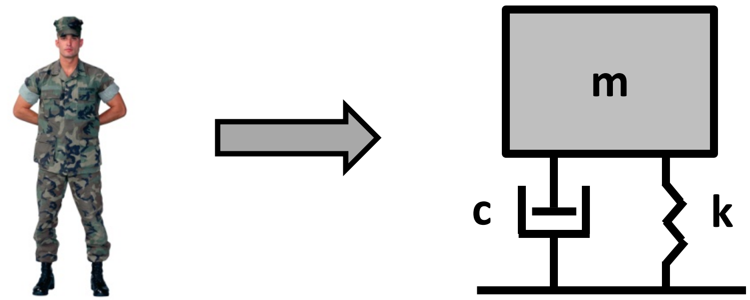
Background

- Various metrics are used to predict the occupant response and evaluate the safety of vehicle designs in underbody blast events.
- Underbody blast events cause a predominant risk of thoraco-lumbar spine injury.
- The Dynamic Response Index (DRI) has been used historically as a metric for spinal compression.



From (NATO, 2007).

Dynamic Response Index (DRI)



- Measure of spinal injury risk that accounts for the time duration of a load.
- Occupant torso modeled as a spring-mass-damper system.
- Calculated from maximum relative displacement between the pelvis and upper torso.

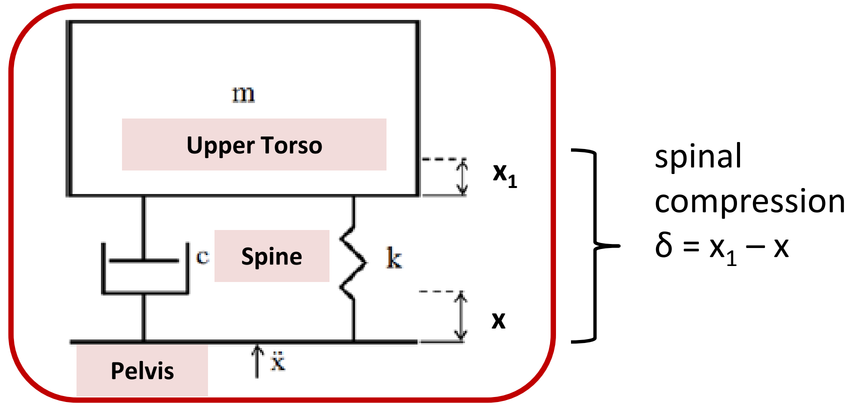
$$DRI = \frac{(\omega_n^2)(\delta_{\max})}{g}$$

ω_n = natural frequency (of spring-mass system)
δ_{max} = maximum relative displacement
g = gravitational acceleration

- Tolerance level of 17.7 for 10% risk of AIS 2+ injuries.

1-DOF model

Takes anthropomorphic test device (ATD) pelvis acceleration or seat acceleration as input (pelvis preferred).



$$m\ddot{x}_1(t) = F_{spring} + F_{damper}$$

$$m\ddot{x}_1(t) = -k(x_1 - x) - c(\dot{x}_1 - \dot{x})$$

$$m(\ddot{\delta} + \ddot{x}) = -k\delta - c\dot{\delta}$$

$$\ddot{\delta} + \ddot{x} = -\frac{k}{m}\delta - \frac{c}{m}\dot{\delta}$$

$$\ddot{\delta} + \ddot{x} = -\omega_n^2\delta - 2\xi\omega_n\dot{\delta}$$

$$\ddot{x} = -\ddot{\delta} - 2\xi\omega_n\dot{\delta} - \omega_n^2\delta$$

$$-\ddot{\boldsymbol{x}}(\boldsymbol{t}) = \ddot{\boldsymbol{\delta}} + 2\boldsymbol{\xi}\boldsymbol{\omega}_n\dot{\boldsymbol{\delta}} + \boldsymbol{\omega}_n^2\boldsymbol{\delta}$$

$$-\ddot{x}(t) = \ddot{\delta} + 2\xi\omega_n\dot{\delta} + \omega_n^2\delta$$

$$DRI = \frac{\omega_n^2\delta_{\max}}{g}$$

- δ is the relative displacement between the upper body and pelvis = **(x_1-x)**
- ζ is the damping coefficient[33] (0.224)
- ω_n is the natural frequency[33] (52.9 rad/s)

ω_n^2 = k/m

$$\xi = \frac{c}{2\sqrt{mk}}$$

1-DOF Computational model

Input time and acceleration
- Time series
- Triangular pulse

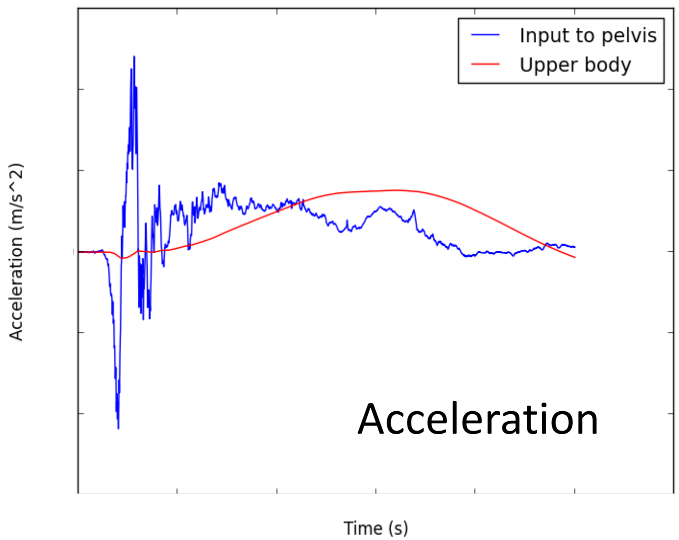
→

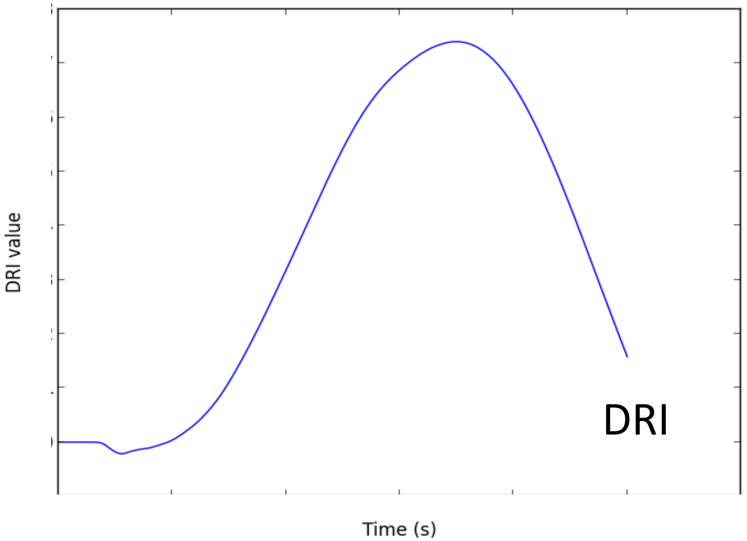
Simulation
- Trapezoidal rule for numerical integration
- Spring and damper forces

→

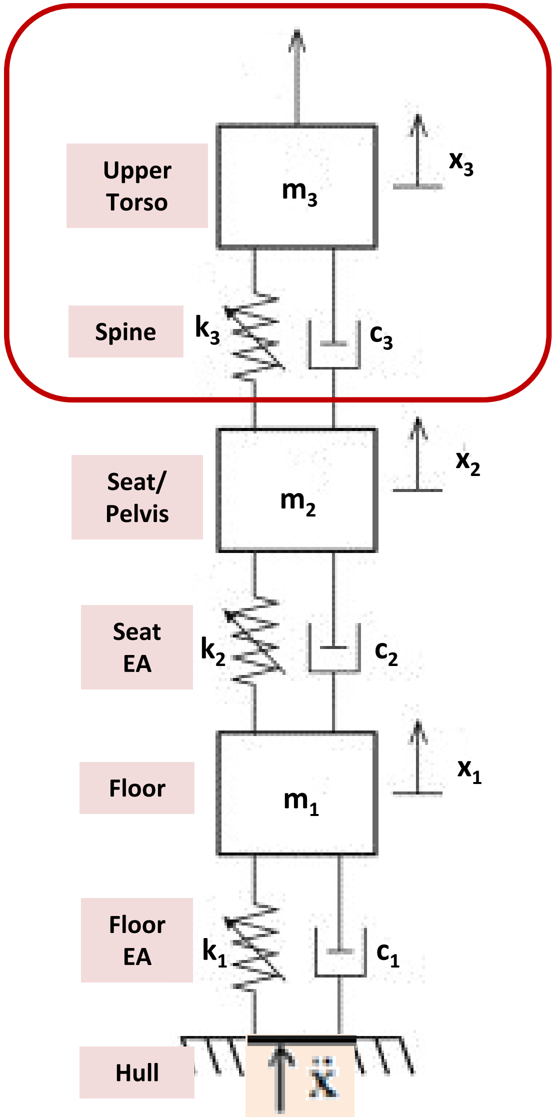
DRI

Acceleration data from physical test:

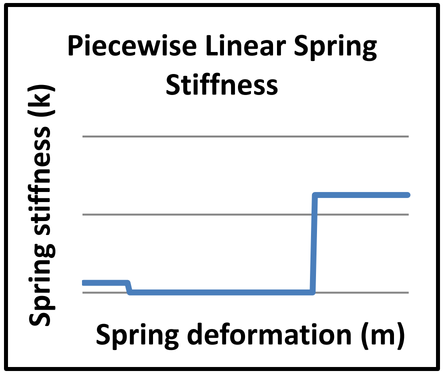




3-DOF model



- Takes hull acceleration as input.
- Accounts for energy absorption by the floor and seat.
- Springs representing the floor and seat are piecewise-linear.
- The spring representing the spine is still linear.



$$m_3\ddot{x}_3(t) = F_{spring3} + F_{damper3}$$
$$m_3\ddot{x}_3(t) = -k_3(x_3 - x_2) - c_3(\dot{x}_3 - \dot{x}_2)$$
$$m_3(\ddot{z}_3 + \ddot{x}_2) = -k_3 z_3 - c_3\dot{z}_3$$
$$\boldsymbol{m_3\ddot{z}_3(t) = -m_3\ddot{x}_2 - k_3 z_3 - c_3\dot{z}_3}$$

$$z_3 = x_3 - x_2$$
$$z_2 = x_2 - x_1$$
$$z_1 = x_1 - x$$

$$m_2\ddot{x}_2(t) = -F_{spring3} - F_{damper3} + F_{spring2} + F_{damper2}$$
$$m_2\ddot{x}_2(t) = k_3(x_3 - x_2) + c_3(\dot{x}_3 - \dot{x}_2) - k_2(x_2 - x_1) - c_2(\dot{x}_2 - \dot{x}_1)$$
$$m_2(\ddot{z}_2 + \ddot{x}_1) = k_3 z_3 + c_3\dot{z}_3 - k_2 z_2 - c_2\dot{z}_2$$
$$\boldsymbol{m_2\ddot{z}_2(t) = -m_2\ddot{x}_1 + k_3 z_3 + c_3\dot{z}_3 - k_2 z_2 - c_2\dot{z}_2}$$

$$m_1\ddot{x}_1(t) = -F_{spring3} - F_{damper3} + F_{spring2} + F_{damper2}$$
$$m_1\ddot{x}_1(t) = k_2(x_2 - x_1) + c_2(\dot{x}_2 - \dot{x}_1) - k_1(x_1 - x) - c_1(\dot{x}_1 - \dot{x})$$
$$m_1(\ddot{z}_1 + \ddot{x}) = k_2 z_2 + c_2\dot{z}_2 - k_1 z_1 - c_1\dot{z}_1$$
$$\boldsymbol{m_1\ddot{z}_1(t) = -m_1\ddot{x} + k_2 z_2 + c_2\dot{z}_2 - k_1 z_1 - c_1\dot{z}_1}$$

3-DOF Computational model

Input time and acceleration
- Time series
- Triangular pulse

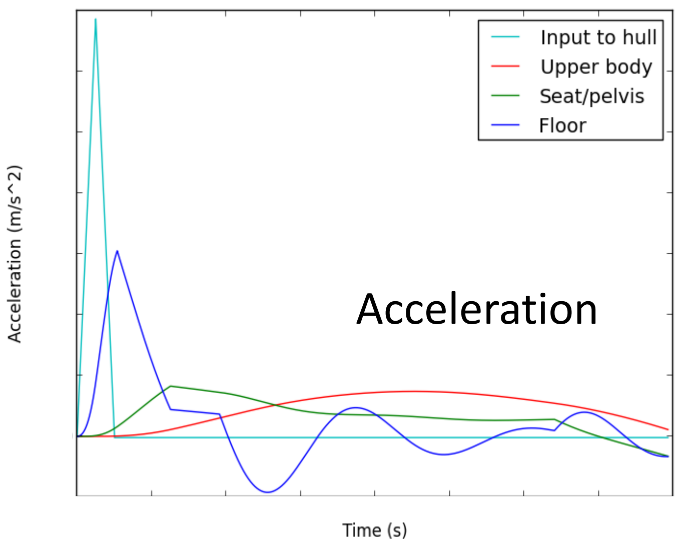
→

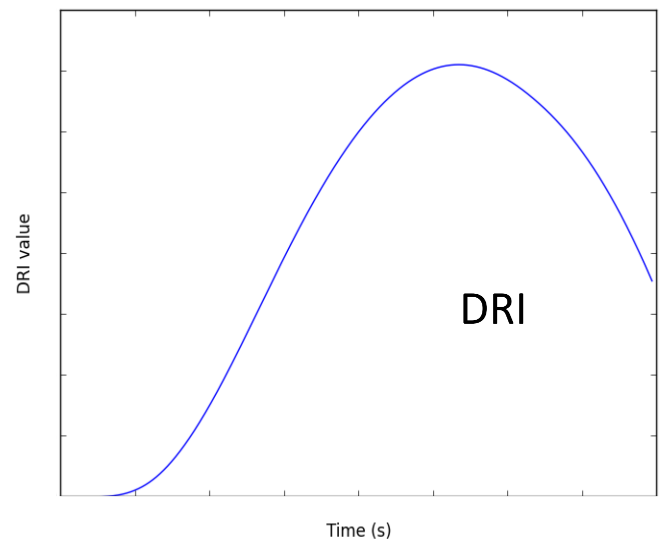
Simulation
- Trapezoidal rule for numerical integration
- Spring and damper forces

→

DRI

Triangular pulse input data (from previously developed Excel code):





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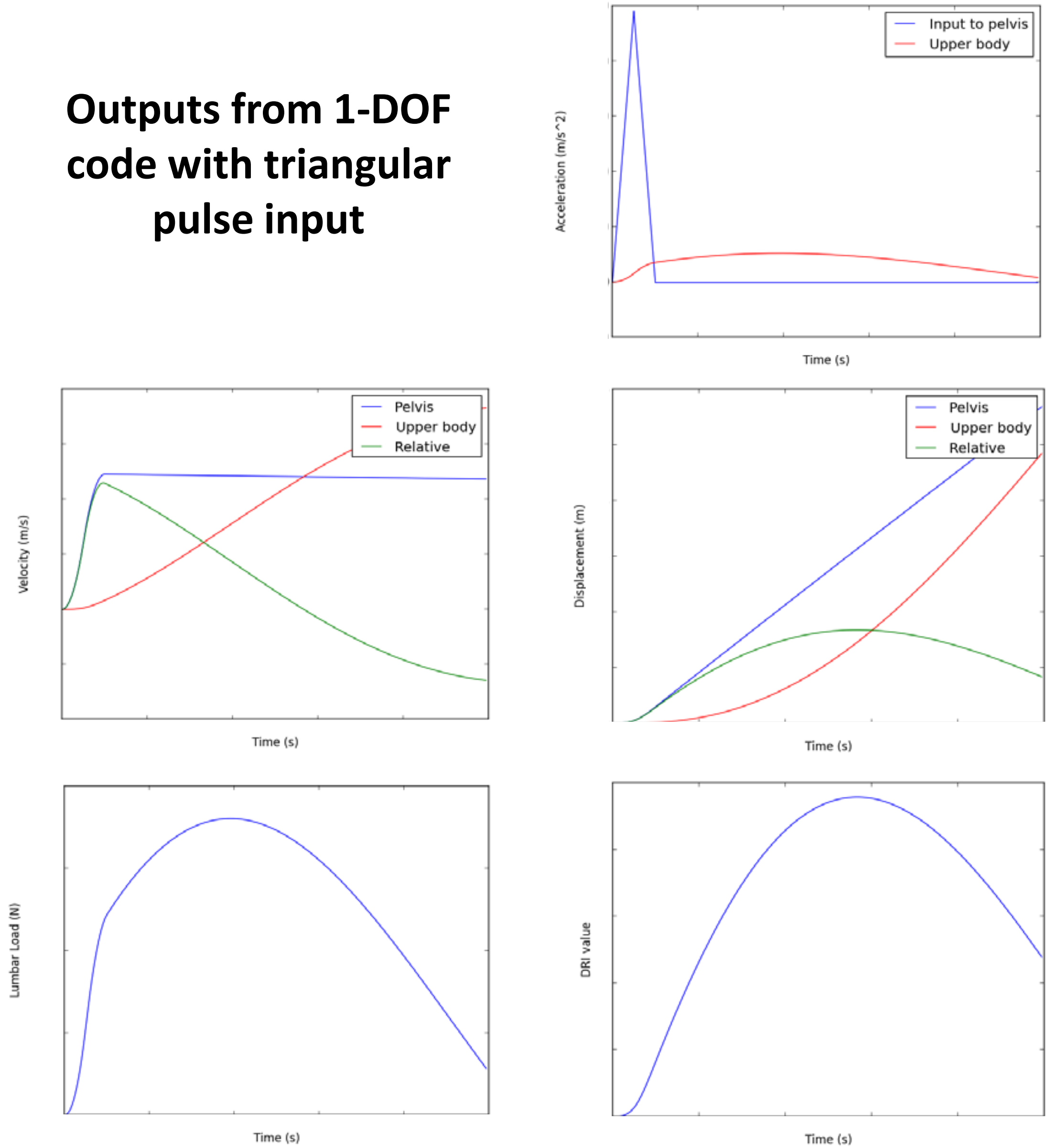
DRI Code

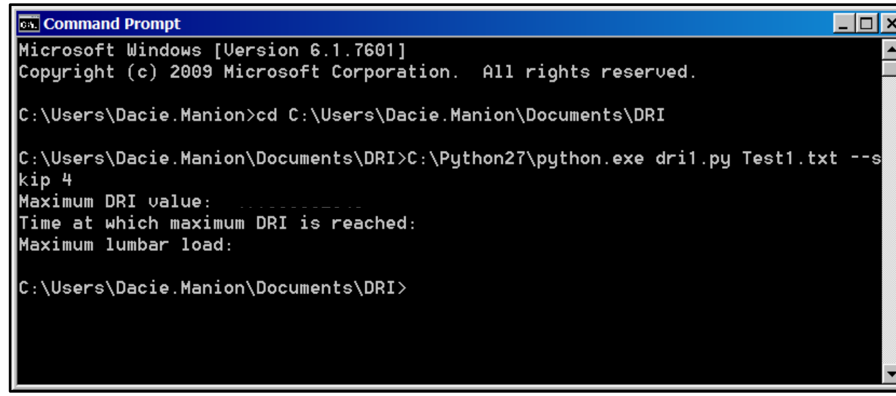
Outputs from 1-DOF code with triangular pulse input

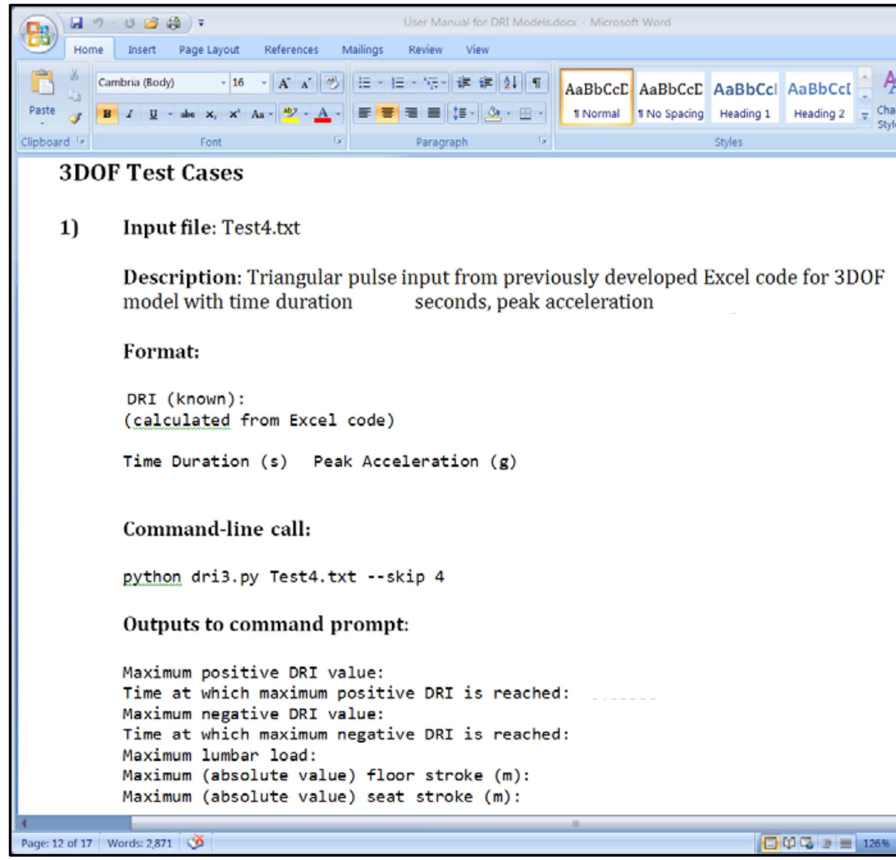
- Written in Python.
  - Requires Python 2.7+ and matplotlib plotting library.
- Executed from command line.
- Allows several optional arguments.
- Runs on Windows, Linux, UNIX, and Mac OS X.



User manual

- Explains input formatting and output files generated.
- Includes example command-line calls and full test cases.
- Test cases used to validate code against:
  - Previously developed Excel code
  - Known DRI values for several physical tests

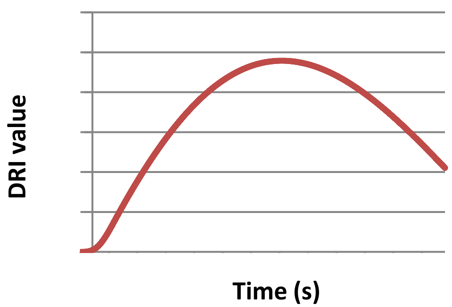




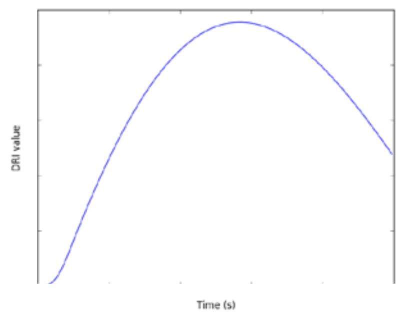
Validation

Triangular pulse input data with given time duration and peak acceleration:

DRI output from Excel:

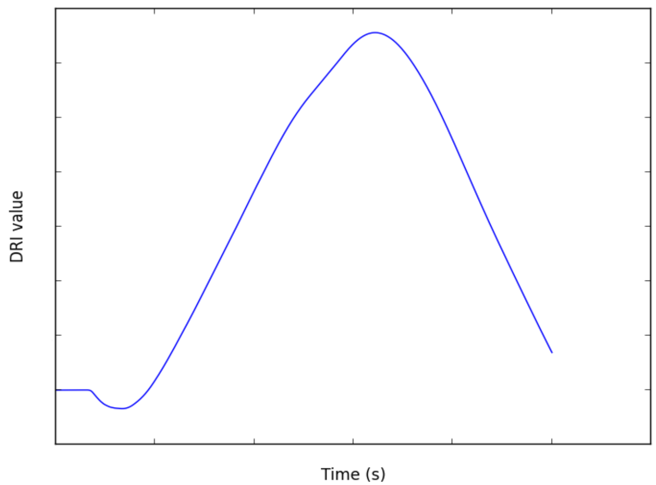


DRI output from Python:



Acceleration data from physical test:

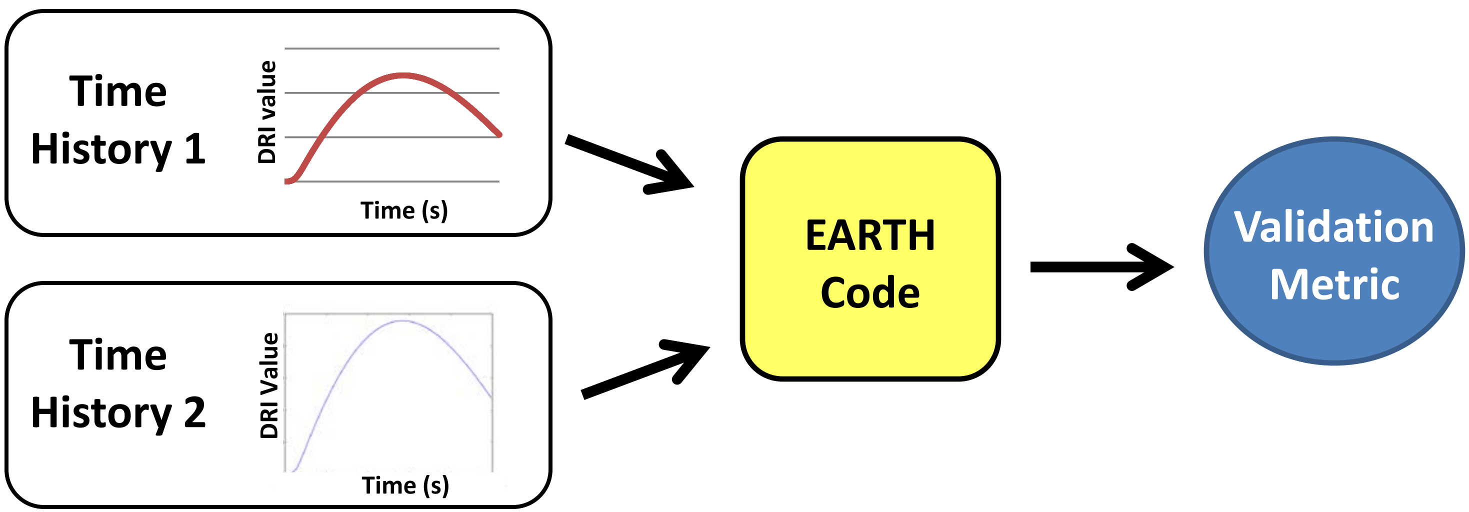
Python output DRI vs. Time:



- Validated against Excel code for both 1-DOF and 3-DOF.
- Used physical test results with DRI calculations previously done in other software to further validate 1-DOF model.
- Validated 3-DOF model against 1-DOF model by setting very large spring constants.

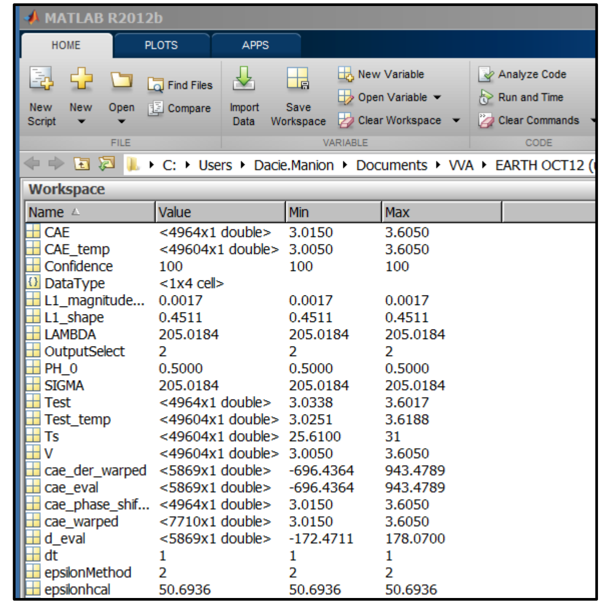
EARTH Code: Motivation

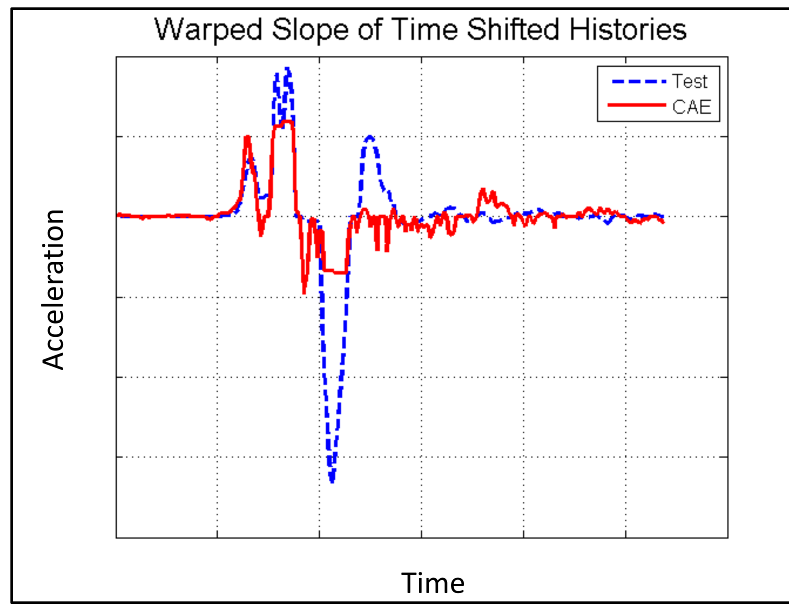
- Error Assessment of Response Time Histories (EARTH)
  - Compares time histories to validate M&S results.
  - New rigorous, quantitative tool for in-house VV&A.
- MATLAB code delivered by the Automotive Research Center (ARC) with several papers but no user manual
  - (Pan, 2012)
  - (Sarin, 2008)
  - (Sarin et al., 2010)



EARTH code

- Combines existing measures and algorithms.
- Quantifies and separates error due to:
  - Phase shift
  - Magnitude differences
  - Topology (shape) discrepancy
- Takes two time histories as inputs along with a few parameters.
- Outputs:
  - Plots of original, shifted, and warped time histories
  - Derivatives of shifted and warped time histories
  - Error metrics for phase, magnitude, and topology
  - Uses Bayesian framework to determine model confidence for original, phase-shifted, warped, and warped derivative data.





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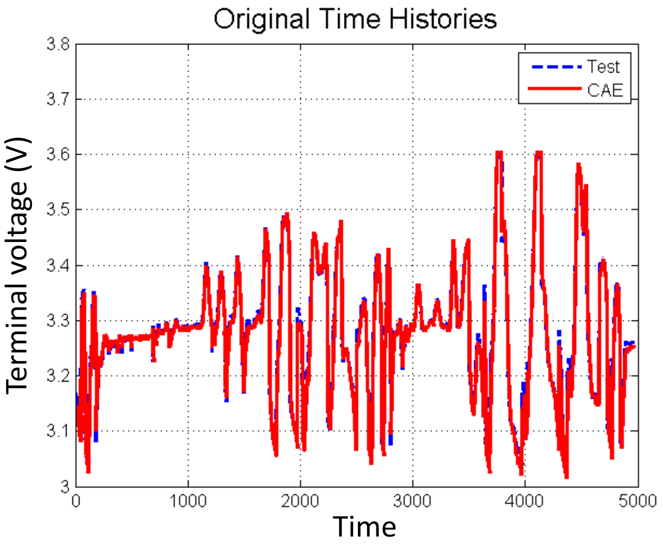
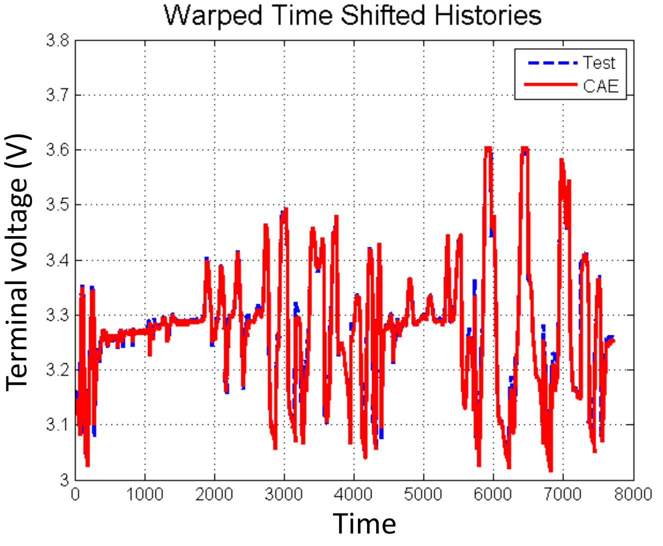
EARTH code validation

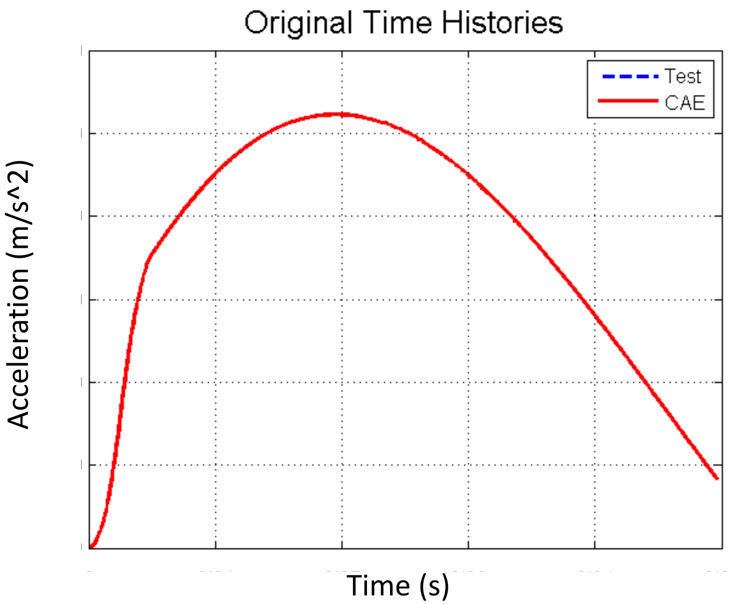
- ARC provided electrothermal battery model example:
  - Test vs. simulation data for terminal voltage.
  - EARTH input parameters.
- Used to ensure code was working properly.
- Results were consistent with those of the ARC (Pan, 2012).

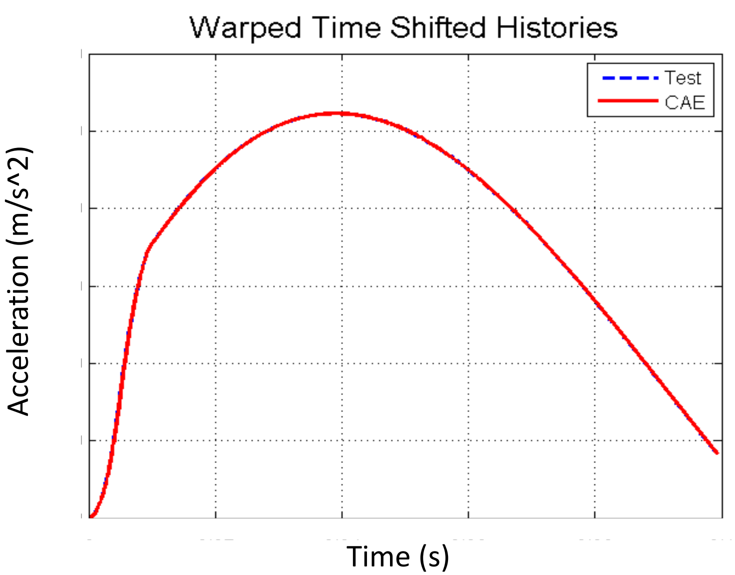
Error Metric	Result
Phase	1
Magnitude	0.0017
Topological	0.4511





Simple test of EARTH code

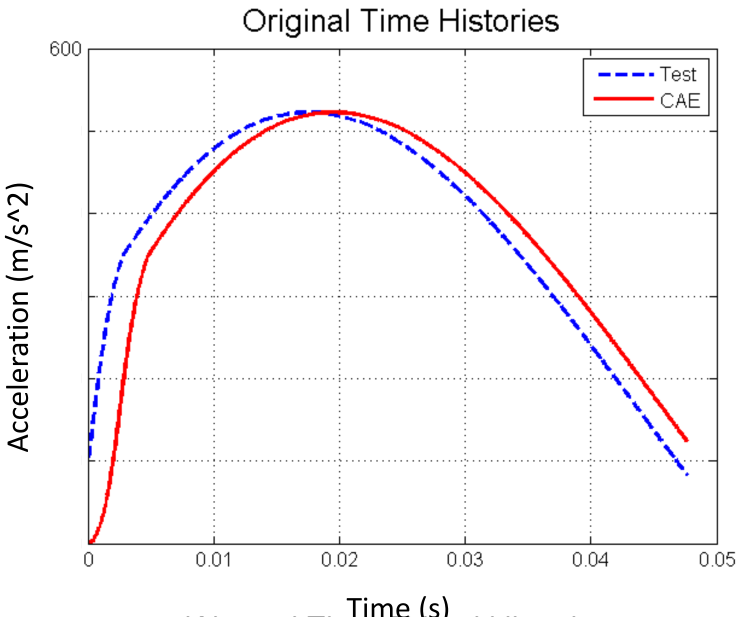


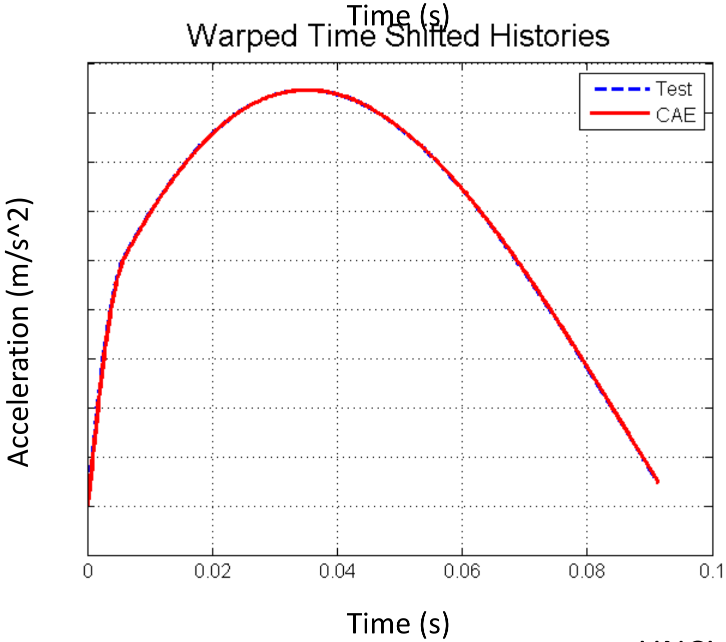


- Compared Excel output vs. Python output for 1-DOF DRI model. Used triangular pulse input data with:
  - Input peak acceleration
  - Input time duration
- Down-sampled from ~25,000 to ~1200 data points to reduce computation time.
- Very low error across each category as expected.

Error Metric	Result
Phase	1
Magnitude	0.0011
Topological	0.0058

Phase shift test of EARTH code



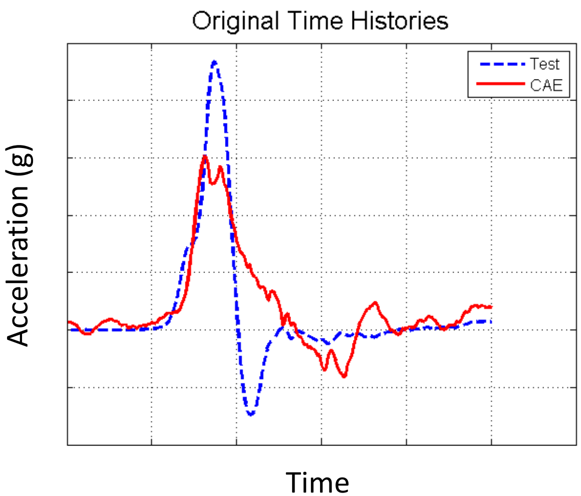


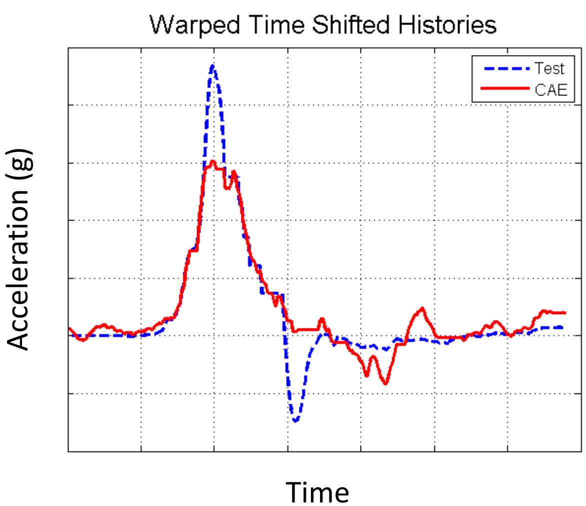
- Introduced a phase shift of 1000 data points in the original vector.
- Down-sampled to ~800 data points. (phase shift of 33)
- EARTH code recognized and handled the phase shift, yielding low magnitude and topological error again as expected.

Error Metric	Result
Phase	34
Magnitude	0.0022
Topological	0.0103

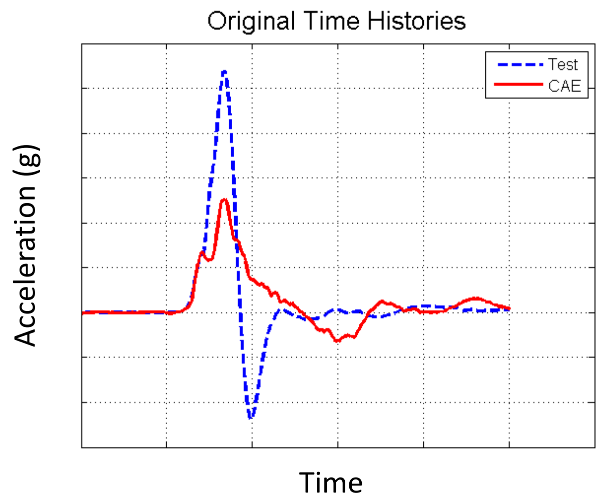
Validation of EECS models

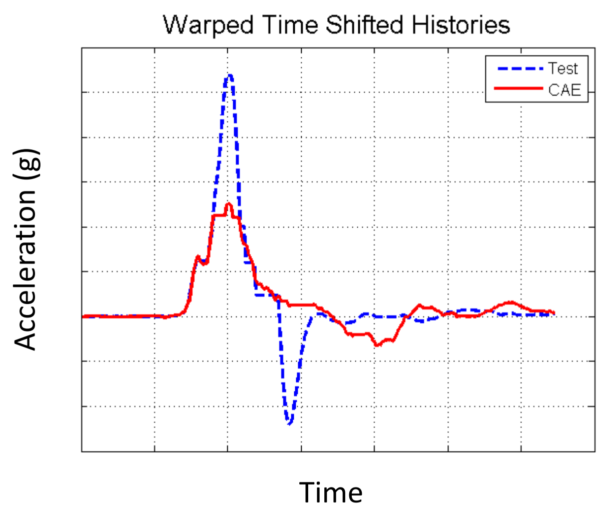
Case 1





Case 2



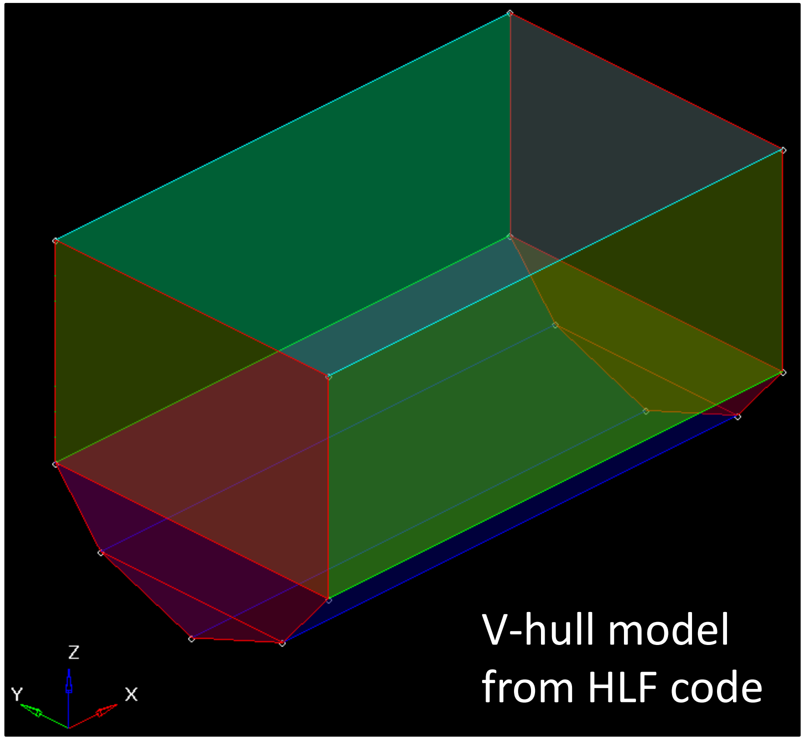


Original data from drop tower tests.

Error Metric	Result
Case 1	
Phase	3
Magnitude	0.4508
Topological	0.7635
Case 2	
Phase	4
Magnitude	0.6779
Topological	0.8296

Ongoing work

- Write EARTH code user manual for in-house use at TARDEC.
- Use DRI code to help evaluate new concept vehicles for DARPA.
- Update Hybrid Lumped-Finite Element (HLF) code (HyperMesh script for generating hull models) to add 3-DOF occupant models.



Summary

1. DRI
   - Developed 1-DOF and 3-DOF code in Python.
   - Validated against Excel code and physical test results.
   - Documented usage and examples.
2. EARTH code
   - Learned and tested EARTH code.
   - Gathered example I/O data.
   - Applied to EECS Team data to support in-house model VV&A efforts.
   - Documented code for future VV&A at TARDEC.
3. Summarized all work in a technical report.

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